Observations on Nuclei Heavier than Iron in the Primary Cosmic Radiation

Rec'd March 9, 1967

by

J.F. Ormes, T. von Rosenvinge
and W.R. Webber

Technical Report
CR-92

January, 1967

School of Physics and Astronomy
University of Minnesota
Minneapolis, Minnesota

Grant NsG-281

Abstract

Systematic studies of the charge and energy spectra of primary cosmic rays with a large area Cerenkov-Scintillation counter on over 10 balloon flights have yielded new limits on the intensity of nuclei significantly heavier than iron. In the course of identifying over 2000 events as due to iron group nuclei, two events which could possibly be related to nuclei with $Z \geq 36$ have been observed. A lower limit of 1000:1 for the ratio of these groups of nuclei is obtained along with an upper limit to the intensity of $Z \geq 36$ nuclei of $4 \times 10^{-8}/\text{cm}^2$-ster-sec. The details of these measurements and some of their astrophysical implications are discussed.

In 1948, photographic emulsion measurements (Freier et.al., 1948, Bradt and Peters, 1948), demonstrated for the first time the presence of nuclei heavier than protons in the primary cosmic radiation. Nuclei from helium (Z = 2), up to at least iron (Z = 26), were found to be present with abundances which, except for notable exceptions such as Li, Be, and B, were quite similar to the known cosmical abundances. In the twenty years that have passed since this discovery, detailed measurements on the charge and energy spectra of these nuclei have been made, generally with two objectives in mind: (1) to determine possible acceleration mechanisms and to study the effects of propagation through interstellar material on the energy spectra of these nuclei, and (2) to localize, if possible, the source regions for acceleration of the cosmic ray nuclei and to study the features of nucleogenisis in these source regions. The second objective requires a detailed knowledge of the charge composition of the cosmic radiation. In this connection the presence and relative abundance of nuclei significantly heavier than iron could provide important clues relating to the method of creation of these nuclei and the nucleogenisis processes in operation in the source regions.

At the present time no direct observations of nuclei heavier than a Z ≈ 30 have been reported using detectors with "good" charge resolution. The extensive body of data on the nuclei up to and including iron allows us to set certain limits on the abundance of the super-heavy (SH) nuclei (Z = 34-40), however, and to delineate features of the charge spectrum in the lower Z range that might assist in the interpretation of any observable intensities of the SH nuclei.

A careful review of the literature up to mid-1965, (Webber, 1966), reveals that ≈ 200 iron group nuclei (imcompassing the charge range Z = 20-28), also called VH nuclei, have been identified in emulsion experiments since heavy nuclei were first discovered. It is reasonable to assume that perhaps another 200 iron group nuclei have been observed in laboratories around the world but not reported in the literature. It is not clear how systematic this search has been or that selection criteria in all of these studies are such that SH nuclei would be observed if they were present. On the basis of the numbers given above, the ratio of VH to SH nuclei in cosmic rays is not less than 400:1.

The typical cosmical abundance of VH to SH nuclei (actually for stars similar to the sun and average hot B type), is ≈ 1000:1, based on an average of four references (Webber, 1966).

In comparing the above ratios one should be cognizant of the widely held viewpoint that heavier nuclei, particularly the VH group, are relatively more abundant in cosmic rays than in cosmic abundance tabulations (up to a factor of 10-30 for VH nuclei). This viewpoint may be somewhat misleading. It is true that, using hydrogen or helium nuclei as a reference, cosmic rays are considerably richer in heavy nuclei than if they were a typical sample of material in the universe. However if one takes the carbon or oxygen nuclei as a reference then the overabundance of VH nuclei in cosmic rays almost (but not completely) disappears (see Webber, 1966). All even nuclei with $Z \geq 6$ in cosmic rays are, in fact, over abundant by approximately the same amount relative to hydrogen or helium nuclei. One might take the alternative viewpoint that hydrogen and helium are relatively less abundant in cosmic rays than in the universe.

Specifically there seems to be no compelling reason to argue that, because of a systematic increase in abundance of heavier cosmic rays relative to cosmical abundances, we should expect a ratio of VH/SH nuclei in cosmic rays considerably less than 1000:1 expected on the basis of cosmilogical abundances. Instead the behavior of the cosmic ray charge abundance for values of $Z \leq 26$ as noted above suggests that this ratio might be expected to be $\approx$ 1000:1 or about the same as the cosmical abundance ratio. Special considerations with regard to nucleogenisis and/or acceleration processes, (eg. Colgate, 1966), may, of course, considerably alter this ratio.

It is into this framework that we wish to introduce our measurements relating to nuclei of the iron group and heavier nuclei. In the course of a systematic study of the charge, energy spectra, and solar modulation effects on nuclei with charge from 1 to 26 we have made a series of more than 10 balloon flights with a Cerenkov-Scintillation counter of geometrical factor $\approx$ 50 st cm^2. In addition, one flight, especially to study heavy nuclei, has been made with an enlarged version of this detector with a geometrical factor $\approx$ 1000 st cm^2. The details of these balloon flights and features of the response of the detectors to heavier nuclei have been discussed (Ormes and Webber, 1966; Webber, Ormes and von Rosenvinge, 1966). Suffice to say here that the charge resolution of the small telescope is such that the pulse heights of relativistic nuclei of each successive charge through $Z \approx 16$ can be identified unambiguously, and for each even charge up through iron. The location of these "peaks" is then referenced to the calibration of the detector system including any possible phototube nonlinearity with light sources. In this way a complete charge calibration for the NE 102 plastic scintillator used in both telescopes can be obtained up through iron. Further details of this charge calibration and extension to still higher charges may be found in a work by Ormes (1966). With the large area detector the energy resolution is insufficient to obtain useful energy spectra, but the charge resolution is $\pm$ 2 charges above Z $\approx$ 20, and sufficient at lower charges to obtain the same direct charge calibration as with the smaller detector. The energy-charge resolution of this large area detector is more than adequate to identify low energy nuclei of a lower charge (iron nuclei) from higher energy nuclei of a higher charge (SH nuclei), however.

The flights with the smaller detector have given a total exposure to primary cosmic rays of 6×10^6 cm^2-ster-sec and have resulted in identification of $\approx$ 550 nuclei of the iron group. One event has been observed that would correspond to a particle of charge 40 ± 1.

The single flight with the large detector had a total exposure of 3.6×10^7 cm^2-ster-sec to the primary radiation. In excess of 1500 nuclei in the iron group were identified on this flight. The observed charge distribution is shown in Figure 1. The observation of events corresponding to charges up to 32 is consistant with the known abundances in cosmic rays up through Z = 28 and the charge resolution of this detector. The event at a Z = 36 can most reasonably be associated with a nucleus of about this charge.

In summary, a total of $\approx$ 2200 nuclei in the iron group have been observed. At most 2 nuclei with $Z \geq 34$ have been identified, giving a lower limit to the VH/SH ratio of 1000:1.

In a counter experiment such as this the presence of a particular type or class particle cannot be confirmed by one event. It is always possible that this event is spurious in one way or another. For example, the event at a charge of 40 could be caused by the interaction, at just the right location in the detector, of a very high energy proton resulting in a meson multiplicity in excess of 150. We estimate the probability of this occuring for our total exposure to be less than 0.01.

We believe that at least one of the SH nuclei observed by us is real, and on this basis obtain a best value for the VH/SH ratio of $2000 \begin{smallmatrix} +2000 \\ -1000 \end{smallmatrix}$ and an intensity of SH nuclei of $2 \pm 2 \times 10^{-8}/cm^2$-ster-sec at the top of the atmosphere.

In Table I we present a comparison of selected cosmic ray nuclei abundances from our measurements with cosmical abundance compilations based on an average of 4 references (Webber, 1966).

The results we report here are in substantial agreement with the preliminary results of Walker et.al. (1966) using a new technique. These workers find that

Table I

Comparative Abundances of Various

Nuclei in Cosmic Rays and in Cosmical Abundance

Compilations

(Normalized at VH nuclei)

Nuclei	Cosmical Abundance (Average of 4 references)	Cosmic Rays	Ratio (CA/CR)
H	4×10^{4}	1800	22
He	4000	240	17
C	9	6	1.5
O	20	5	4
VH (Z=20-28)	1	1	1
SH (Z=34-40)	8×10^{-4}	$<5 \times 10^{-4}$	<1.6
Z=52-56	5×10^{-5}	-	-
Z=76-78	1×10^{-5}	-	-
Z=82	3×10^{-6}	-	-

It should be noted that differences of a factor of 3-4 for element abundances exist in different compilations. The abundances represent averages for solar type stars and must be adjusted according to theories of nucleogenisis for classes of stars in earlier or later stages of development.

certain crystals in meteoritic material show evidence for damage which is most probably caused by stopping VH or SH nuclei. These crystals behave somewhat like very insensitive nuclear emulsions which have had exposure times equal to the lifetimes of the meteorite. As a consequence there are large numbers of tracks in very small volumes of crystal. We quote from a summary of their paper by Waddington (1966), "As yet Walker et.al. have been unable to calibrate this technique and as a result they did not wish to quote a value for the relative abundance for the $Z \geq 30$ nuclei, however, examination of their data suggests that the ratio of VH nuclei to still heavier nuclei is about 10,000:1." In view of the uncertainties, this value is not inconsistant with ours, and the two measurements taken together demonstrate that the relative abundance of nuclei heavier than iron in cosmic rays is at least as small or smaller than the cosmical abundance ratio of these groups of nuclei.

Measurements relating to charges with $Z \geq 30$ have also been reported by Ginsburg et.al. (1963). Using a single Cerenkov detector with levels set to record pulses greater than those from a relativistic nucleus with $Z = 15$ and $Z = 30$-40 the above workers find one event above the upper threshold for approximately 1000 above the lower threshold during observations from three satellites.

It is of some interest to note that a model for the supernova origin of cosmic rays by Colgate (1966) would predict that the ratio of VH to SH nuclei in cosmic rays should be enhanced over the ratio of these nuclei in cosmic abundance table by approximately the ratio in which the VH nuclei are enhanced relative to protons and helium in cosmic rays. A VH/SH ratio $\simeq 1000 \times (10$-$30) = 1$-$3 \times 10^4:1$ might be expected on these grounds. Our results, while giving a somewhat lower ratio than this, are certainly not inconsistant with it. If cosmic rays were samples of material that had evolved through the r process then the abundance of nuclei heavier than iron might be enhanced by several fold over the normal cosmic abundances. The observed high VH/SH ratio tends to rule out this possibility.

The authors wish to thank P. Fowler for stimulating us to write up this work. This research was supported by NASA grant NSG-281-62.

Figure Captions

Figure 1 Charge distribution of cosmic ray events observed during balloon flight of large area detector.

References

Bradt, H.L., and Peters, B., 1948, Phys. Rev., 74, 1828.

Colgate, S.A., 1966, Proc. 9th Int. Conf. on Cosmic Rays, London, 1, 112.

Freier, P., Lofgren, E.J., Ney, E.P., and Oppenheimer, F., 1948, Phys. Rev., 74. 1818.

Ginsburg, V.L., Kurnosova, L.V., Razorenor, L.A., and Fradkin, M.L., 1963, Space Sci. Reviews, 2, 778.

Ormes, J.F., and Webber, W.R., 1966, Proc. 9th Int. Conf. on Cosmic Rays, London, 1, 349.

Ormes, J.F., M.S. Thesis. University of Minnesota, 1966.

Waddington, C.J., 1966, Proc. 9th Int. Conf. on Cosmic Rays, London, 1, 462.

Walker, R.M., Fleischer, R.L., and Price, P.B., 1966, Proc. 9th Int. Conf. on Cosmic Rays, London, 2, 1086 (abstract).

Webber, W.R., Ormes, J.F., and von Rosenvinge, T., 1966, Proc. 9th Int. Conf. on Cosmic Rays, London, 1, 407.

Webber, W.R., 1966, to be published in Hdb. d. Phys., Vol. 46/2, (Berlin: Springer-Verlag).

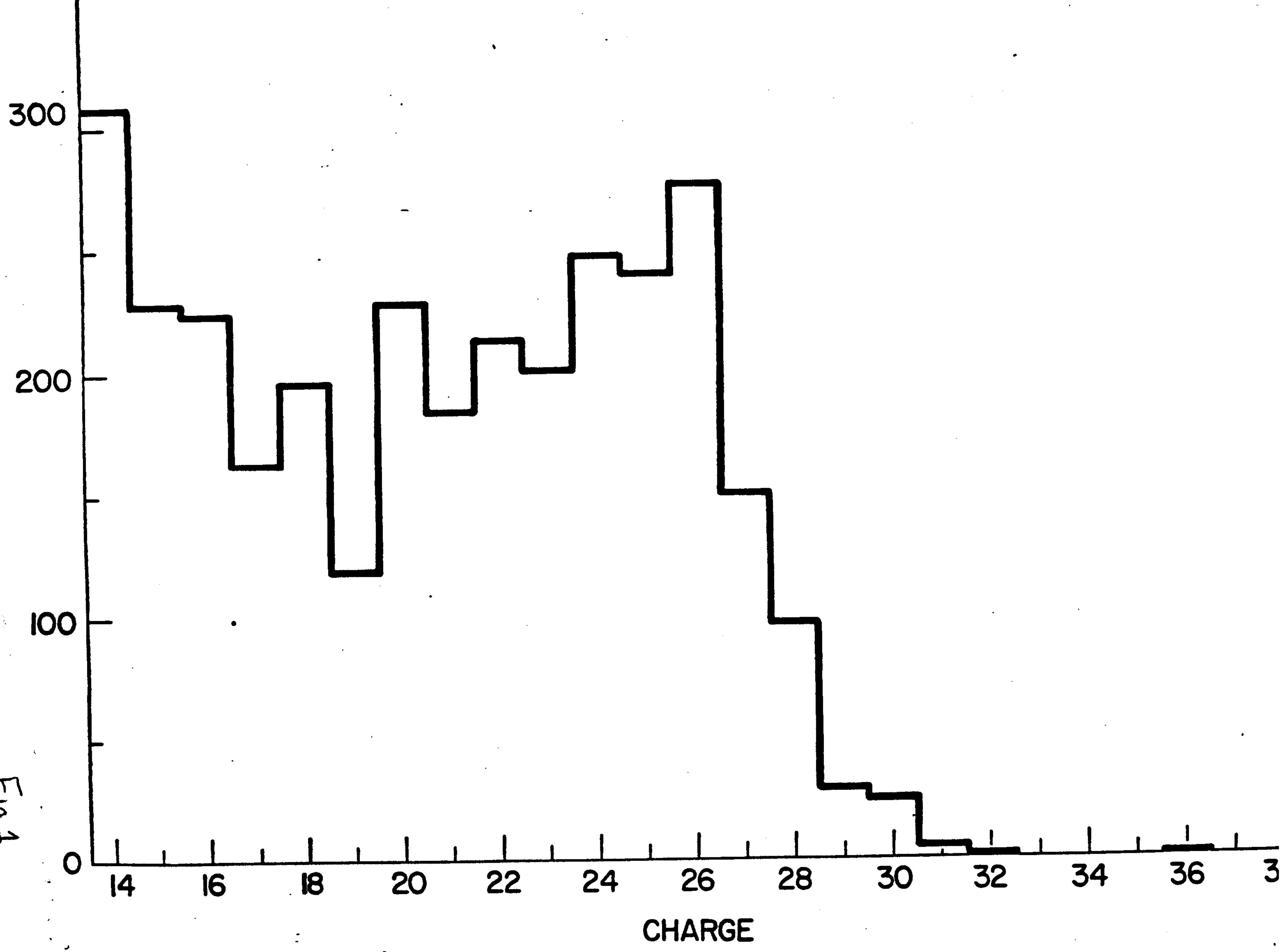

Fig 1